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DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA

Propulsion Technical Memorandum 453

THE DEVELOPMENT OF A T53-L11 ENGINE COMPUTER MODEL

by

J. FARAGHER

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SUMMARY

This Technical Memorandum describes the development of a steady-state engine model for a Lycoming T53 turboshaft engine. A genuine compressor map obtained from Lycoming was integrated into a generic gas turbine modelling program called Turbotrans. Both engine performance predictions and the variation of output power with free turbine speed showed good correlation with manufacturer's data. The ability to simulate engine wear and damage via degraded component efficiencies was demonstrated but not validated.

DSTO ARL MELBOURNE

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CONTENTS

NOMENCLATURE

Stations

1	Compressor inlet
2	Compressor outlet/Combustor inlet
3	Combustor outlet/Gas Generator Turbine inlet
4	Gas Generator Turbine outlet/Free Turbine inlet
5	Free Turbine outlet

Engine Quantities

N1	Gas Generator Speed (100% = 25150 r.p.m.)
N2	Free Turbine Speed (100% = 21085 r.p.m.)
η_c	Compressor Isentropic Efficiency
η_t	Turbine Isentropic Efficiency
C_{pa}	Specific Heat of Air
C_{pg}	Specific Heat of Combustion Gases
γ_a	Ratio of Specific Heats for Air = 1.4
γ_g	Ratio of Specific Heats for Combustion Gases = 1.33
T_0	Total Temperature
P_0	Total Pressure
P_a	Ambient Pressure
ΔT_{012}	Temperature Rise Across Compressor
ΔT_{034}	Temperature Drop Across Gas Generator Turbine
ΔT_{045}	Temperature Drop Across Free Turbine
P_{02}/P_{01}	Compressor Pressure Ratio
P_{03}/P_{04}	Gas Generator Turbine Pressure Ratio
P_{04}/P_{05}	Free Turbine Pressure Ratio
$\frac{m \sqrt{T_{01}}}{P_{01}}$	Corrected Mass Flow at Compressor Inlet
$\frac{m \sqrt{T_{03}}}{P_{03}}$	Corrected Mass Flow at Gas Generator Turbine Inlet

1.0 INTRODUCTION

ARL task (86/038) Gas Turbine Performance Analysis involves the investigation of gas turbine engine performance and stability margins when components are degraded. Turboshaft engines used in helicopters which operate in harsh environmental conditions are subject to dust and sand ingestion which causes erosion of compressor and turbine blades and deposition of fine particles in both the compressor and the turbines. Both effects raise the compressor running line and reduce the surge margin so that, ultimately, the engine cannot be accelerated from idle to full power without the possibility of surging.

This Technical Memorandum describes the development of a steady-state engine performance model with component degradation capability for a Lycoming T53 turboshaft engine. The results of this study will be used in an experimental programme on the T53 engine for assessing component degradation and its affect on overall performance levels and surge margins.

A further significance of this work is that the Lycoming T53 engine, whilst not being as complex as the GE T700 is similar in aerothermodynamic configuration to it : the GE T700 engine is used in the Black Hawk and Seahawk helicopters recently acquired by the Australian Services, and the results of the studies can be applied to this more modern engine.

2.0 THE LYCOMING T53-L11 TURBOSHAFT ENGINE

The Lycoming T53 series of engine was designed in the late 50's and early 60's as a rugged power unit for military helicopters. It has been extensively used in the US Army, and Royal Australian Air Force, and is installed in several models of the Bell UH-1 Iroquois helicopter. ARL has acquired two complete engines, and spares, for experimental testing and is currently setting up a rig engine.

2.1 Engine Configuration

The Lycoming T53-L11 turboshaft engine has one compressor and two single stage turbines. The compressor comprises five axial stages followed by one centrifugal stage. The first turbine drives the compressor while the second turbine is a free turbine driving the output shaft via a reduction gearbox. The combustor is an

external, reverse flow, annular, vaporizing type. Maximum power at sea level is 1100 s.h.p..

Interstage air bleed is provided between the axial and centrifugal stages of the compressor to prevent surging at low speeds and during transient engine operation. Loosening a circular band around the engine, which covers a row of bleed holes, allows air to be bled off from the compressor. Variable inlet guide vanes are not incorporated in the L11 version of the T53 engine.

A picture of the T53-L11 engine is shown in Figure 1, and a schematic diagram of the T53-L11 engine showing the station numbers is shown in Figure 2.

3.0 ENGINE MODELLING

Engine Performance Group at ARL has access to a number of specific and generic engine computer models. The generic models include DYNGEN, MODENG and TURBOTRANS. The specific models (GEF404 and GET700) are available only in object or machine code; these codes cannot be modified and have no facility for modelling degraded components. Consequently there is a need to develop in house both steady state and dynamic engine models in which component characteristics can be varied, and their effect on outputs observed.

3.1 The Turbotrans Program

A generic gas turbine modelling program called Turbotrans is available at ARL for the simulation of gas turbine behaviour. The program was developed at Cranfield Institute of Technology, England and is written in Fortran. It follows closely the format of the NASA DYNGEN program but has much more flexible input procedures. The program can be run in a steady state or dynamic mode by inclusion of the appropriate fuel control system. It can be used to model many different configurations of gas turbine engines with varying numbers of compressors and turbines. The aerothermodynamic behaviour of the engine is determined from component "characteristic maps" of the compressors and turbines. A user may select a component map which comes with the program or insert a map which is more representative of the component being modelled. More information about the program and its structure is given in Appendix 1.

3.2 Lycoming T53 Steady State Model

3.2.1 Design Point Data

The basic input for the T53 model was the design operating point data at sea level which was obtained from the Lycoming T53-L11 model specification [1].

These data values were:

Compressor speed (N1) = 97.8% (100% = 25150 rpm)
Free Turbine speed (N2) = 100% (100% = 21085 rpm)
Compressor Pressure Ratio = 6.2
Mass Flow = 10.7 lbs/sec
Output Power = 1070 shp.

These design point values were used as the starting point for all runs of the T53 simulation.

3.2.2 Free Turbine Speed

A turboshaft engine, in contrast to a simple turbojet engine, extracts power from the turbine to drive the load. In the case of the T53 engine the load or helicopter rotor blades are driven by a free power turbine which can be scheduled to run at a fixed or variable speed. The T53 specification document defines an optimum free turbine speed as the free turbine speed which, for a given gas generator speed, gives the maximum output power. The variation of optimum free turbine speed with gas generator speed for the T53-L11 engine is given in Figure 3, and shows that the optimum free turbine speed decreases as the gas generator speed decreases. This variation in optimum free turbine speed is inconsistent with helicopter operations which normally use constant speeds for the rotor. Notwithstanding this the data from Figure 3 have been used in the T53 model to enable a more direct comparison to be made between model results and specification data. The effect of constant free turbine speed on engine performance is discussed in section 4.

3.2.3 Air Bleed

For the current work the compressor has been modelled as a single component. A single map describes the characteristics of the entire compressor.

Gas conditions are calculated only at the inlet and the outlet and not between stages. Thus, it is not possible to model interstage air bleed, where some of the air is removed at a point between the axial and centrifugal sections of the compressor. However, future work with the T53 simulation will involve the generation of the compressor characteristic map or maps from the characteristics of the individual stages using a "stage-stacking" procedure. The compressor may then be modelled as two or more components and air bleed extraction between the axial and centrifugal sections may then be modelled.

Interstage air bleed is not a concern for the calculations in this Technical Memorandum since all calculations are for steady state conditions with gas generator speeds greater than 80%. Under these conditions the bleed band is always closed.

3.3 Turbotrans T53 Simulation with Turbotrans Maps

Initially, Lycoming component maps were not available for use in modelling the T53 engine. So generic maps that came with the Turbotrans program were used for the compressor and turbines.

The Lycoming T53-L11 model specification provided data for mass flow, fuel flow, engine speed and shaft horsepower. These data were displayed graphically and compared with the Turbotrans output to see how close the Turbotrans predictions were to the known data from the Lycoming model specification.

All calculations in this Technical Memorandum are for a stationary engine at sea level on a standard day. Therefore all data are normalized or corrected data.

During some experimentation with the Turbotrans program to discover which quantities could be specified to define an off-design operating point for the engine, the following combinations were successfully used:

a. fuel flow and shaft horsepower;
b. turbine inlet temperature and shaft horsepower;
c. fuel flow and free turbine speed; and
d. gas generator speed and free turbine speed.

Since the relationship between gas generator speed and free turbine speed was available (Figure 3) it was convenient to use these two quantities to define the off-design operating points of the engine. Output power, mass flow and fuel flow were calculated by the program once the engine model had been balanced at each new set of speeds.

The results of a typical run of the Turbotrans program are shown in Figures 4, 5 and 6. The Lycoming model specification data are plotted on the same graphs for comparison. These results were very good considering how little genuine Lycoming information was used to customize the generic Turbotrans model into a specific T53 simulation.

3.4 The Turbotrans T53 Simulation with Lycoming Compressor Map

Part way into the project an actual T53 compressor map was obtained from the engine manufacturer, Lycoming. The main difference between the two compressor maps was in the shape of the constant corrected speed lines on the pressure ratio vs. corrected mass flow plot and in the values of corrected speed at corresponding corrected mass flow - pressure ratio points. The lines on the Turbotrans map were quite straight and almost vertical. On the Lycoming map, however, they curved over to become almost horizontal at the surge line, reflecting the low stage loading of each compressor stage, and the old design technology used in the T53 engine (see Figure 10).

3.4.1 Engine Performance Predictions with the Lycoming Compressor Map

Typical plots of output power, mass flow and fuel flow against gas generator speed are given in Figures 7, 8 and 9 for the T53 simulation using the Lycoming compressor map. The manufacturer's data are also plotted on these Figures for comparison. The off-design results were obtained by specifying gas generator speed and optimum free turbine speed.

It can be seen that the Turbotrans engine performance predictions were very close to the manufacturer's data. This was particularly pleasing since Turbotrans maps were being used for the turbine simulation: it has not been possible to obtain actual turbine maps from Lycoming.

The output power and mass flow predictions were very close to the Lycoming data across the whole speed range. The fuel flow predictions were very close to the Lycoming data at high speeds but diverged slightly from these data as the gas generator speed dropped to eighty percent. The fuel flow predictions were not as close to the specification data when the Lycoming map was used as when the Turbotrans map was used. The percentage differences between the specification data and the simulation results for output power, mass flow and fuel flow at a gas generator speed of 90% were 8.9%, 2.9% and 1.2% respectively using the Turbotrans compressor map, and 0.0%, 0.1% and 6.0% respectively using the Lycoming compressor map. Further refinement to the model would be needed to improve these results - particularly, some Lycoming data for the turbines.

3.4.2 The compressor running lines

A free-turbine turboshaft engine, under steady state conditions, like a single spool turbojet engine, is constrained to operate on a single line on the compressor characteristic map and will not depart from this line whatever happens to the load on the engine provided the final nozzle or turbine is choked and component efficiencies are not degraded. This is in contrast to a single spool turboshaft engine which can operate in many different places on the compressor map depending upon the load-speed characteristics of the load placed upon it, for instance a propeller or an electrical generator.

Using the same design point, and specifying the off-design operating points with the same gas generator and free turbine speeds, running lines were generated using first the Turbotrans and then the Lycoming compressor maps. The two running lines thus generated were nearly coincident despite the differences in the compressor maps. That is, when the engine model was balanced, almost identical pressure ratios and corrected mass flows were calculated by the two models at different engine speeds (see Figure 10).

At low values of corrected mass flow, the surge line occurred at lower pressure ratios on the Lycoming compressor map than on the Turbotrans compressor map. Since the two running lines were coincident, the surge margin for the running line on the Lycoming compressor map, at low values of corrected mass flow (and hence at low speeds), is much smaller than the surge margin, in this region, on the Turbotrans compressor map. The small surge margin at low speeds explains why the

manufacturers have had to incorporate interstage air bleed at low speeds to prevent surging.

3.4.3 Coincidence of Running Lines

The fact that the running lines almost coincided despite the differences in the compressor maps can be explained in the following way.

If for any given pressure ratio in the normal operating region of the engine the corrected compressor mass flow can be approximated as being independent of speed, and only a function of component efficiencies, which can also be approximated as being independent of speed, then its clear why the two running lines that have been generated are nearly coincident. This can be demonstrated in the following way.

a. At any given point of corrected mass flow and pressure ratio on the compressor running line, the difference in corrected speed between the Turbotrans and Lycoming compressor maps is small - between three and five percent For both maps, efficiency varies only slightly with speed. Thus, at any given point on the running line, the difference in efficiency between the two maps is very small.

b. When the speed of either turbine varies about its normal operating point, only small changes in turbine efficiency result. These changes in turbine efficiency cause much smaller changes in turbine temperature ratio. Thus, in the normal operating region, the turbine efficiency and corrected mass flow (which is a function of the square root of the temperature ratio) can be approximated as being independent of speed .[1] Each turbine characteristic map can then be drawn as a single curve relating the corrected mass flow at the turbine inlet to the turbine pressure ratio.

That the corrected mass flow at the compressor inlet can be calculated without knowing the engine speed, provided the above approximations are made, can be shown as follows.

1 See Cohen, Rogers and Saravanamuttoo. Section 8.4.

c. The corrected mass flow at the outlet of the gas generator turbine is the corrected mass flow at the inlet of the free turbine. Under the above approximations, it is a function of the corrected mass flow at the gas generator turbine inlet and the gas generator turbine pressure ratio. Thus, it can be calculated for any given point on the gas generator turbine characteristic. It can then be used with the free turbine characteristic to find the free turbine pressure ratio.

Since both turbine pressure ratios are now known, and the pressure loss in the combustor is assumed to be a constant fraction of the combustor inlet pressure, the compressor pressure ratio may be determined using the relation.

$$\frac{P_{02}}{P_{01}} = \frac{P_{03}}{P_{04}} \times \frac{P_{04}}{P_a} \times \frac{P_{02}}{P_{03}} \qquad (P_{01} = P_a)$$

where $\frac{P_{03}}{P_{04}}$ = gas-generator turbine pressure ratio

$\frac{P_{04}}{P_a}$ = free turbine pressure ratio

$\frac{P_{03}}{P_{02}}$ = pressure ratio across combustor

Then, assuming the compressor efficiency varies very little with small changes in speed (a. above) we can use

$$\frac{\Delta T_{012}}{T_{01}} = \frac{1}{\eta_c}\left[\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

where ΔT_{012} = temperature rise across the compressor

T_{01} = temperature at compressor inlet

η_c = compressor isentropic efficiency

$\frac{P_{02}}{P_{01}}$ = compressor pressure ratio

γ_a = 1.4

to find the temperature rise across the compressor.

Then, to find the temperature drop across the gas generator turbine as a fraction of the temperature at the inlet to the gas generator turbine, assuming turbine efficiency is independent of speed (b. above), we can use

$$\frac{\Delta T_{034}}{T_{03}} = \eta_t \left[1 - \left(\frac{P_{04}}{P_{03}}\right)^{\frac{\gamma - 1}{\gamma}} \right]$$

where ΔT_{034} = temperature drop across the gas generator turbine

T_{03} = temperature at inlet to gas generator turbine

η_t = gas generator turbine isentropic efficiency

$\frac{P_{03}}{P_{04}}$ = gas generator turbine pressure ratio

γ_g = 1.33

Then, to find the gas generator turbine inlet temperature, we can use

$$\frac{T_{03}}{T_{01}} = \frac{\Delta T_{012}}{T_{01}} \times \frac{T_{03}}{\Delta T_{034}} \times \frac{C_{pa}}{C_{pg}}$$

where C_{pa} = specific heat of air

C_{pg} = specific heat of the combustion gases

(In this simple analysis both C_{pa} and C_{pg} have been assumed invariant with gas temperature).

Then, to find the corrected compressor mass flow, we can use

$$\frac{m\sqrt{T_{01}}}{P_{01}} = \frac{m\sqrt{T_{03}}}{P_{03}} \times \frac{\sqrt{T_{01}}}{\sqrt{T_{03}}} \times \frac{P_{02}}{P_{01}} \times \frac{P_{03}}{P_{02}}$$

where $\dfrac{m\sqrt{T_{01}}}{P_{01}}$ = corrected mass flow at the compressor inlet

$\dfrac{m\sqrt{T_{03}}}{P_{03}}$ = corrected mass flow at the gas generator turbine inlet

From the above equations it can be seen that if the compressor and turbine efficiencies are approximated as being independent of speed (a. and b. above) then the engine speed will not come into the calculations at all. Hence for a given compressor pressure ratio the same corrected compressor mass flow will be calculated despite differences in compressor speed. This is what has been observed in Figure 10. While the compressor and turbine efficiencies in the T53 simulation are not independent of speed, they do, as mentioned above, vary very little with speed. Hence the two running lines generated are almost coincident.

4.0 THE EFFECT OF FREE TURBINE SPEED ON OUTPUT POWER

As indicated in section 3 it is possible to run the Turbotrans T53 simulation with a constant gas generator speed and vary the free turbine speed. By doing this a plot of output power against free turbine speed can be obtained for various gas generator speeds. From this plot, for any gas generator speed, it is clear what free turbine speed gives the maximum output power. Plots of this form are useful for comparing the performance of the engine with various load-speed applications.

The net power output of a free turbine turboshaft engine is simply the output of the power turbine.

That is, output power = $mC_{pg}\ \Delta T_{045}$

where $\Delta T_{045} = \eta_t T_{04} \left[1 - \left(\dfrac{P_a}{P_{04}} \right)^{\frac{\gamma - 1}{\gamma}} \right]$

Since the free turbine efficiency will vary significantly with large changes in free turbine speed, so will the output power.

A plot of output power against free turbine speed, for gas generator speeds down to eighty percent, is shown in Figure 11. From this plot it is clear that output power drops markedly at low free turbine speeds. The discontinuities in the plots are due to problems encountered during interpolation of efficiency values at intermediate engine speeds and flow functions (Figure 13).

For gas generator speeds of 97.8% and 95% the maximum output power occurs at the maximum free turbine speed. As gas generator speed is decreased the maximum value of output power for each gas generator speed occurs at progressively lower values of free turbine speed. This supports the concept of an optimum free turbine speed at any gas generator speed. The Lycoming model specification data for optimum free turbine speed from Figure 3 has also been plotted on Figure 11 for comparison.

For gas generator speeds of 97.8% and 80% Figures 12 and 13 show how the enthalpy drop across the free turbine and the free turbine efficiency decrease at low free turbine speeds.

5.0 COMPONENT EFFICIENCY DEGRADATION

Operating turboshaft engines in helicopters in harsh environmental conditions results in dust and sand ingestion causing erosion of compressor and turbine blades and deposition of fine particles in both the compressor and the turbines. This results in the degradation of component efficiency leading to reduced engine performance and the possibility of surging.

Surging is a phenomenon, which occurs in the compressor, characterized by a sudden drop in compressor delivery pressure and violent aerodynamic pulsations which can be transmitted through the whole engine. Engine surging may be avoided by means of interstage air bleed in the compressor. This is incorporated in the T53 engine but with degraded components this bleed may not be sufficient to prevent surging. If nothing is done to repair the degraded components the engine will eventually become inoperable.

Surging can be caused by stalling of the aerofoil shaped compressor blades which like any aerofoil may stall at high angles of attack due to flow separation. The angle of attack of the compressor blades is determined by the mass flow and rotational speed of the compressor. Decreased mass flow, due to compressor degradation, at any particular rotational speed (i.e. raising the compressor running line) increases the angle of attack of the blades. The greater the degradation of the compressor the further the operating conditions become from those for which the compressor blades were designed and the greater the likelihood of stalling, and hence the greater the risk of surging.

It is possible with the Turbotrans program to model components with degraded efficiencies in order to simulate wear or damage in the engine. After running the Turbotrans program with degraded component efficiencies it was found that degraded compressor and turbine efficiencies in the gas generator tended to shift the compressor running line towards the surge line - reducing the surge margin. If degradation in the efficiencies of these components causes the compressor running line to intersect the surge line at low speeds, it then becomes impossible to bring the engine up to full power from idle. Slightly less degradation than this still poses a problem since during rapid acceleration the engine departs from the equilibrium running line on the compressor characteristic map and moves closer to the surge line. If the running line intersects the surge line during transient operation the engine will surge.

Figure 14 shows how the equilibrium compressor running line moves towards the surge line on the compressor characteristic map when the efficiencies of the compressor and turbine in the gas generator are degraded by five percent. The surge line would also drop, but it is not possible in the current computer model to predict or even simulate this effect. It is anticipated that with the incoporation of a stage stacking compressor model both variation in surge line position, and individual stage degradation can be incorporated in the Turbotrans simulation.

Since the Turbotrans T53 simulation, as it presently stands, does not include interstage air bleed, it is impossible to determine whether the bleed used would be sufficient to prevent the surging of an engine with degraded components. However, work currently underway at ARL should make this possible in the near future.

Also, since only steady-state engine operation has been considered to date, the deviation from the equilibrium compressor running line under transient conditions (such as accelerating the engine rapidly up to full power from idle) and the likelihood of this leading to compressor surge in an engine with degraded components are matters that will be covered in future work.

6.0 CONCLUSIONS

6.1 Initial customization of the generic gas turbine modelling program, Turbotrans, to model the Lycoming T53-L11 turboshaft engine has been very successful.

6.2 A genuine compressor map obtained from Lycoming has been integrated into the program.

6.3 Minor modifications have been made to overcome some of the problems encountered while running the program.

6.4 Engine performance predictions have shown good correlation with manufacturer's data over the entire range studied. A sole exception is fuel flow which showed a 6.0% discrepency at a gas generator speed of 90%.

6.5 Variation of output power with free turbine speed has been investigated and shown to be comparable with manufacturer's specifications for optimum free turbine speed. That is, it was shown that as gas generator speed decreases, maximum output power is obtained for a free turbine speed of less than 100%.

6.6 The ability to simulate engine wear and damage via component efficiency degradation has been demonstrated, but not validated. The surge line would be expected to drop as compressor efficiency is degraded but this cannot be simulated or demonstrated. However, the running line was shown to move towards the surge line, as expected, with degraded compressor efficiency.

6.7 Future development of stage-stacking techniques to synthesize the compressor map from its individual stages will allow interstage air bleed to be modelled and and the effect of degradation of individual compressor stages to be investigated.

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APPENDIX 1. THE TURBOTRANS PROGRAM

THE MODEL

A steady-state thermodynamic model of a Lycoming T53-L11 turboshaft engine has been created. The basis of this model is a computer program called "Turbotrans" written at Cranfield Institute of Technology, England. It is written in fortran and runs on the ELXSI computer at ARL. Turbotrans is a generic gas turbine model which can be adapted to model many different configurations of gas turbine with varying numbers of compressors and turbines.

BRICKS

The "customisation" of the Turbotrans program, to model a particular engine, is achieved by executing various parts of the program in an appropriate order. Each part of the program is called a "brick" and corresponds to a component of the engine such as the inlet duct, compressor, turbine, etc.

STATION VECTORS

The various bricks are linked together with station numbers, so that the outlet conditions from one brick become the inlet conditions for the next brick. The full set of conditions at the entry or exit of any component, i.e. at any station, is called the "station vector".

BRICK DATA

Each brick requires certain data to be specified at the design point. This information, known as "brick data", includes values such as compressor pressure ratio, engine speed and fuel flow.

VARIABLES

When off-design steady-state results are calculated, some items of brick data will remain fixed at their design point values. Other items of brick data may be allowed to "float" and will be calculated in the process of balancing the engine model. These items are called "variables" and must be designated as such by the user. Items

designated as variables must not be given a value in the off-design cases. Thus, the choice of variables will be influenced by which items the user wishes to use to define the off-design running points.

COMPONENT "MAPS"

The characteristics of various components are determined from component "maps". These maps consist of sets of values of parameters which are representative of a particular component and which can be plotted against each other to give a graph whose shape describes the behaviour of that component. To reduce the computer memory space required to store the map the number of points is kept to a minimum. Values in between given points are found by interpolation using similar triangles.

Where there is a sharp turn in a curve, and only a small number of data points, problems can arise in the interpolation process giving erroneous results. For this reason the compressor map was increased from five points per constant speed line to ten points per constant speed line. Although this change to the compressor map didn't appear to make any significant change to the results, it safeguards against the possibility of interpolation errors.

The combustor and convergent nozzle have one map each. The program user has no access to these maps without changing the fortran program itself. There are five compressor maps and five turbine maps presented in Turbotrans which under analysis reduce to two compressor maps and two turbine maps. When the user specifies a compressor or turbine brick in the program, one of the items of brick data required is the number of the map to be used with this brick. Alternatively, the user may insert a new map for a compressor or turbine, which is known to represent a component of the particular engine being modelled.

SCALE FACTORS

The component maps are scaled by the Turbotrans program to suit the brick data design point values. The scale factors then remain fixed throughout the off-design calculations.

ERRORS

The Turbotrans program "guesses" values for the variables and calculates "errors" for certain engine components. An "error" is the fractional difference between a value calculated from thermodynamic laws using data based on the "guessed" quantities and a value obtained from the component characteristic map using the same data. The values of the variables are adjusted during the balancing process to reduce the size of the "errors". The engine model is considered balanced when the values of all "errors" have been reduced below a certain tolerance.

The "errors" in the model indicate:

1. discontinuities in the mass flow through the engine;

2. a power imbalance between the turbine and compressor sharing the same shaft; and

3. a difference between the actual pressure and the required pressure at the nozzle inlet.

It is unfortunate that these quantities have been given the ambiguous name of "errors". They should not be confused with other kinds of errors which stop the program running (see section A2.2).

APPENDIX 2. PROBLEMS WITH TURBOTRANS

A2.1 Discontinuous Results

When the calculated shaft-horsepower was plotted against engine speed it was sometimes found to follow a smooth curve for a certain distance and then jump to some new operating point before continuing on a new smooth curve. This discontinuity was found to be due to a part of the turbine subroutine which increased the corrected mass flow by one percent if the turbine outlet pressure fell below one hundred and three percent of the ambient pressure. Unfortunately, due to the nature of the turbine characteristic map being used to find the enthalpy drop across the turbine, a one percent increase in corrected mass flow resulted in a twenty eight percent increase in the enthalpy drop across the turbine. Hence the jump in output power.

This problem occurs only when modelling turboshaft engines, since it is only in turboshaft engines that the turbine outlet pressure likely to be very near to ambient pressure. When this section of the turbine subroutine was removed the program ran without any problems and produced smooth, continuous results.

A2.2 Error Messages

Sometimes the program would stop in the middle of an off-design calculation and the computer generated an error message, such as, "floating point - invalid operation". However, if off-design data very slightly different from that being used was chosen, the problem could often be avoided.

Similarly, the message, "engine has not converged after 20 loops", which is generated by the Turbotrans program itself, to limit the length of calculations, can be avoided by using slightly different input off-design data.

A2.3 Points to Watch

Two basic points to watch to ensure successful running of the turbotrans program are:

a. an item specified as a "variable" at the beginning of the program cannot then be given a value in the off-design data; and

b. the number of "variables" specified by the user must equal the number of "errors" generated by the program.

Picture of a T53-L11 Turboshaft Engine.

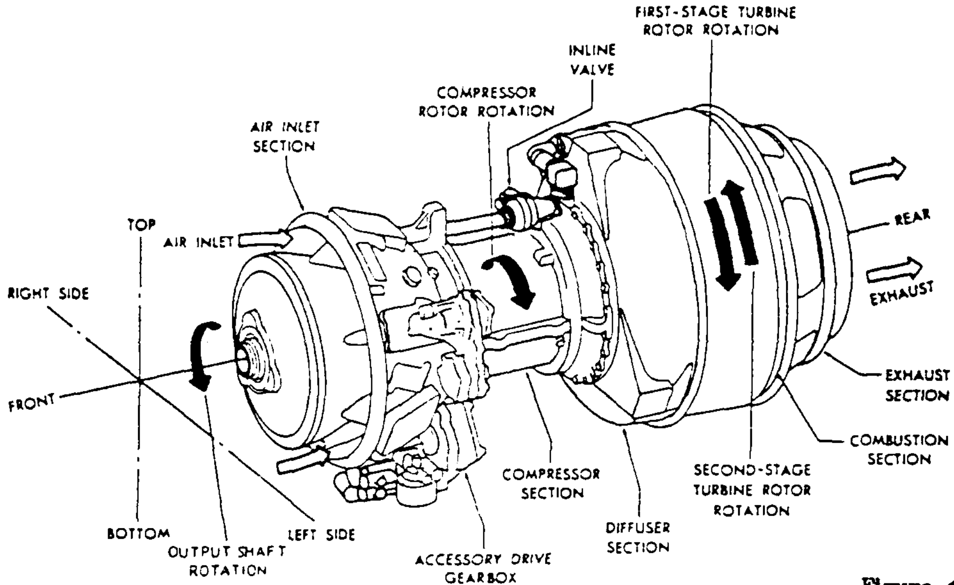


Figure 1

Schematic Diagram of T53-L11 Turboshaft Engine.

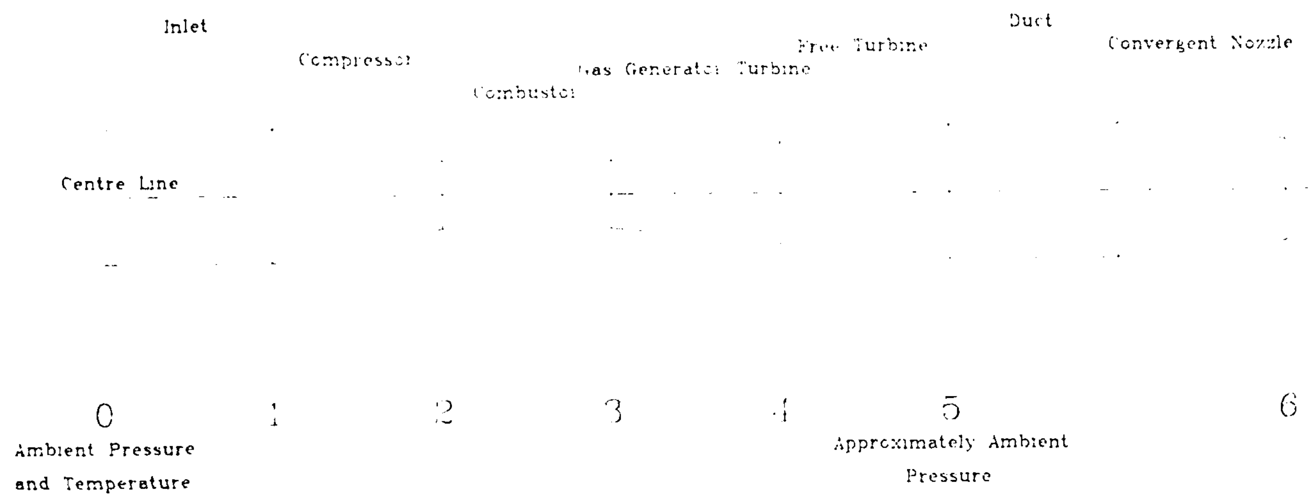


Figure 2

Optimum Free Turbine Speed vs. Gas Generator Speed

(from Lycoming specification data)

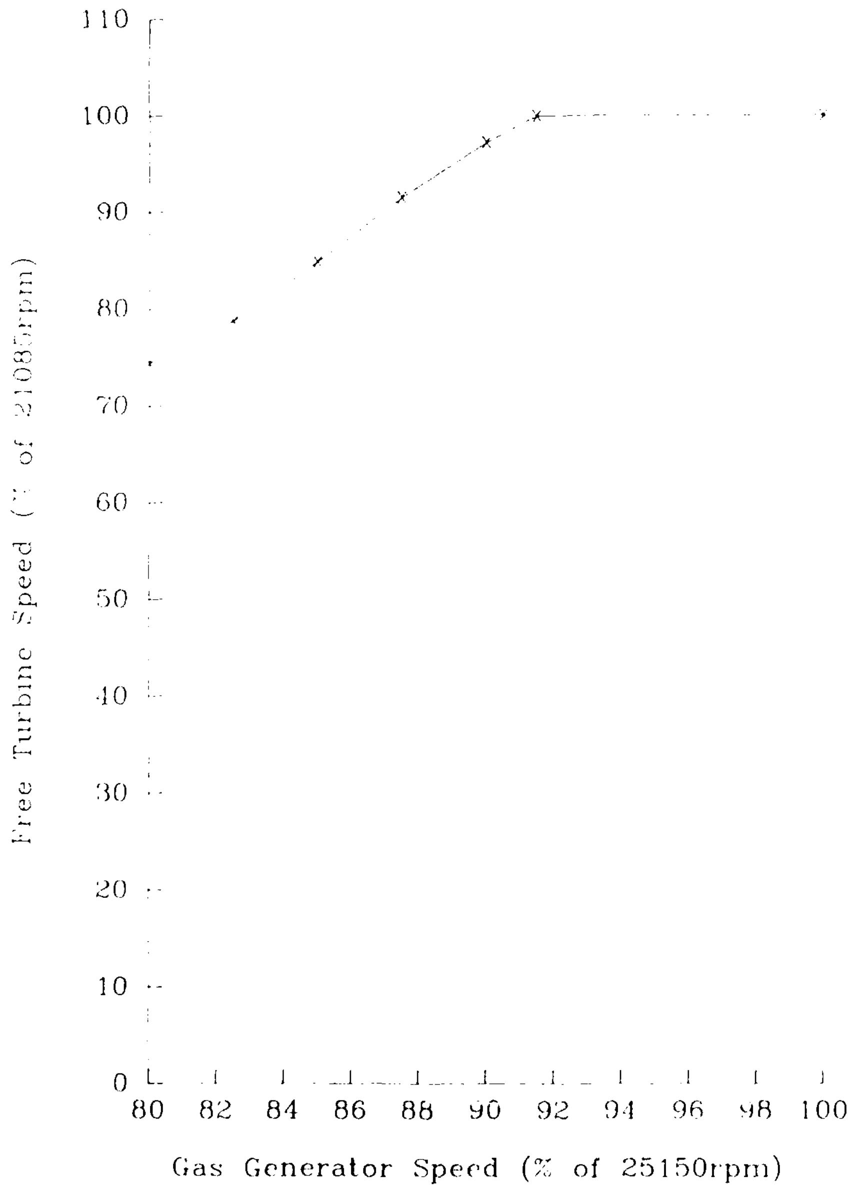


Figure 3

Output Power vs. Gas Generator Speed

(using Turbotrans compressor map)

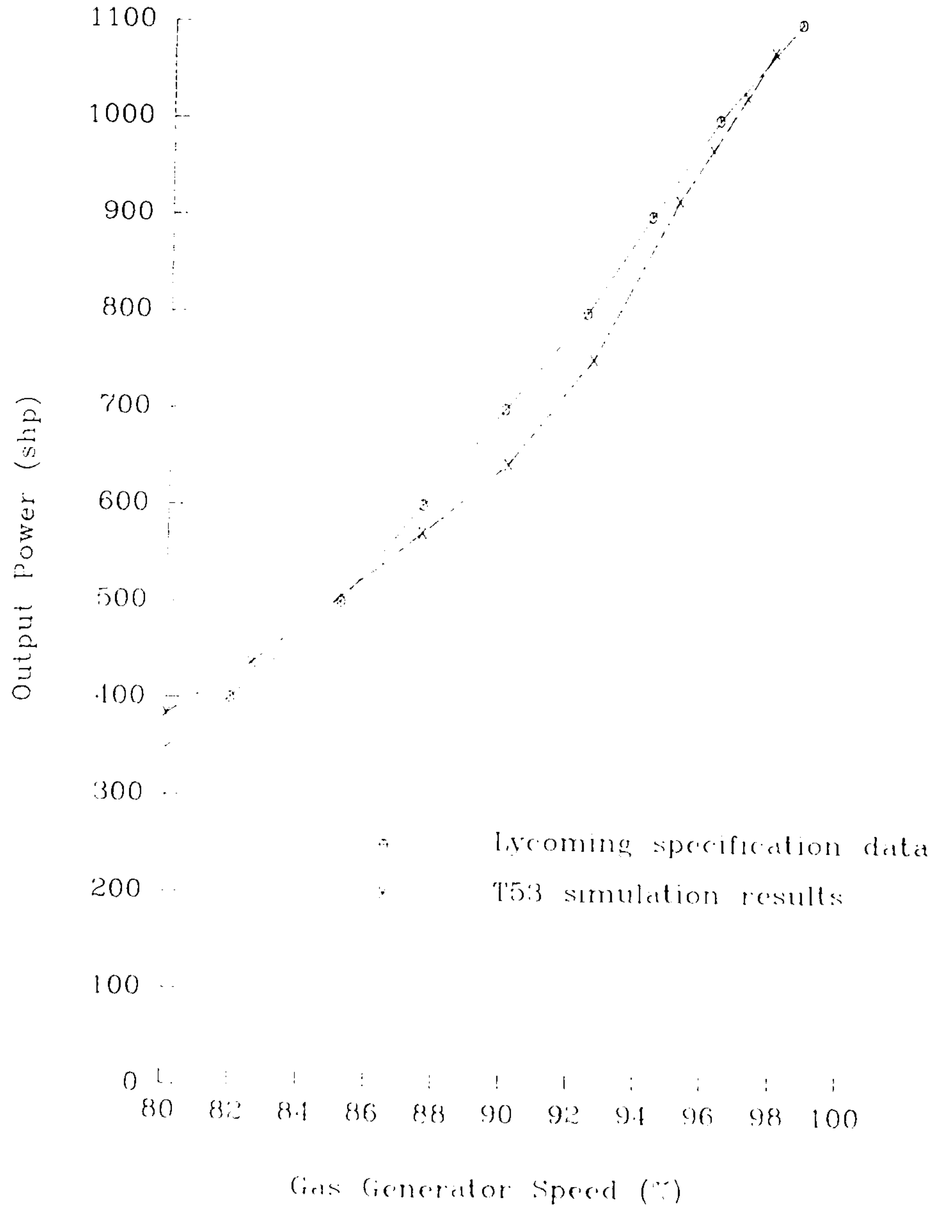


Figure 4

Mass Flow vs. Gas Generator Speed

(using Turbotrans compressor map)

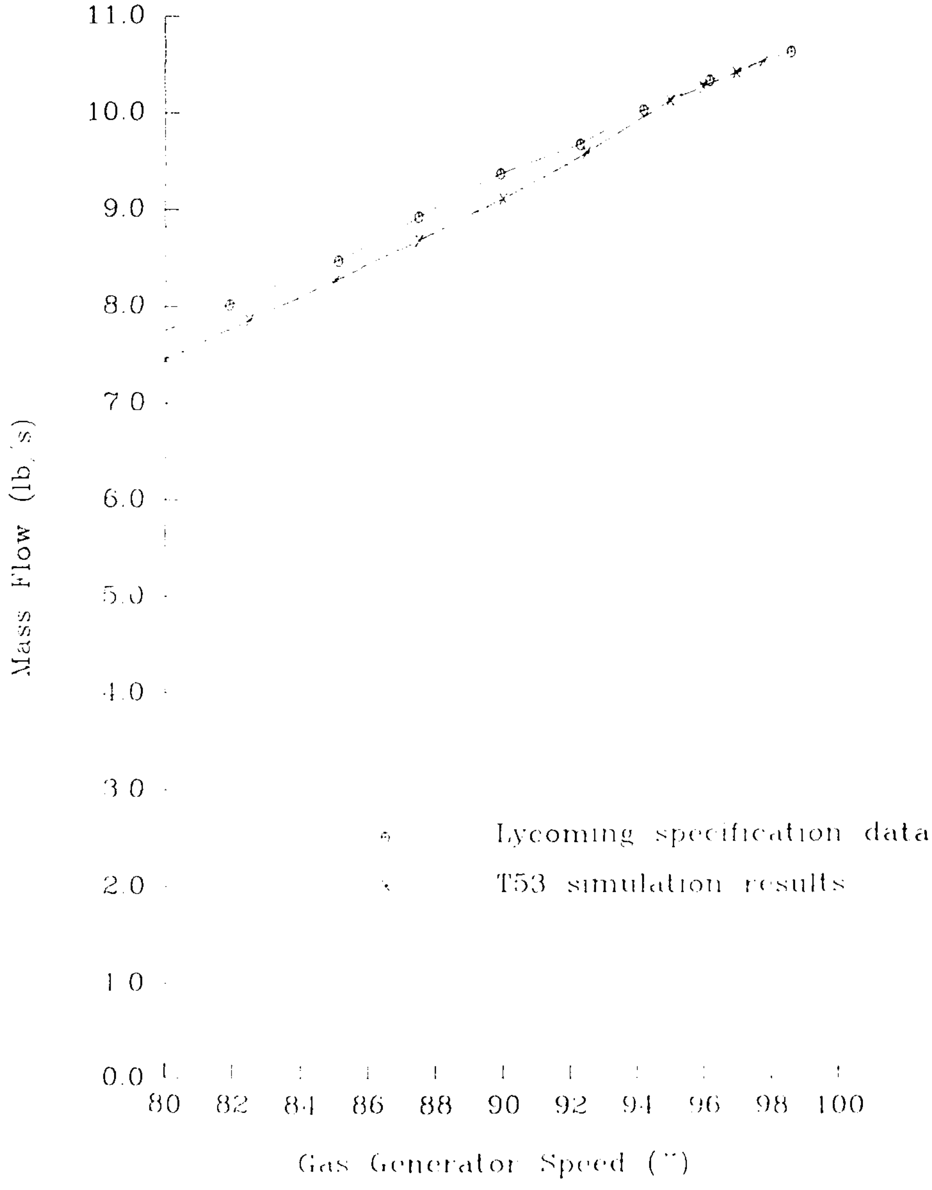
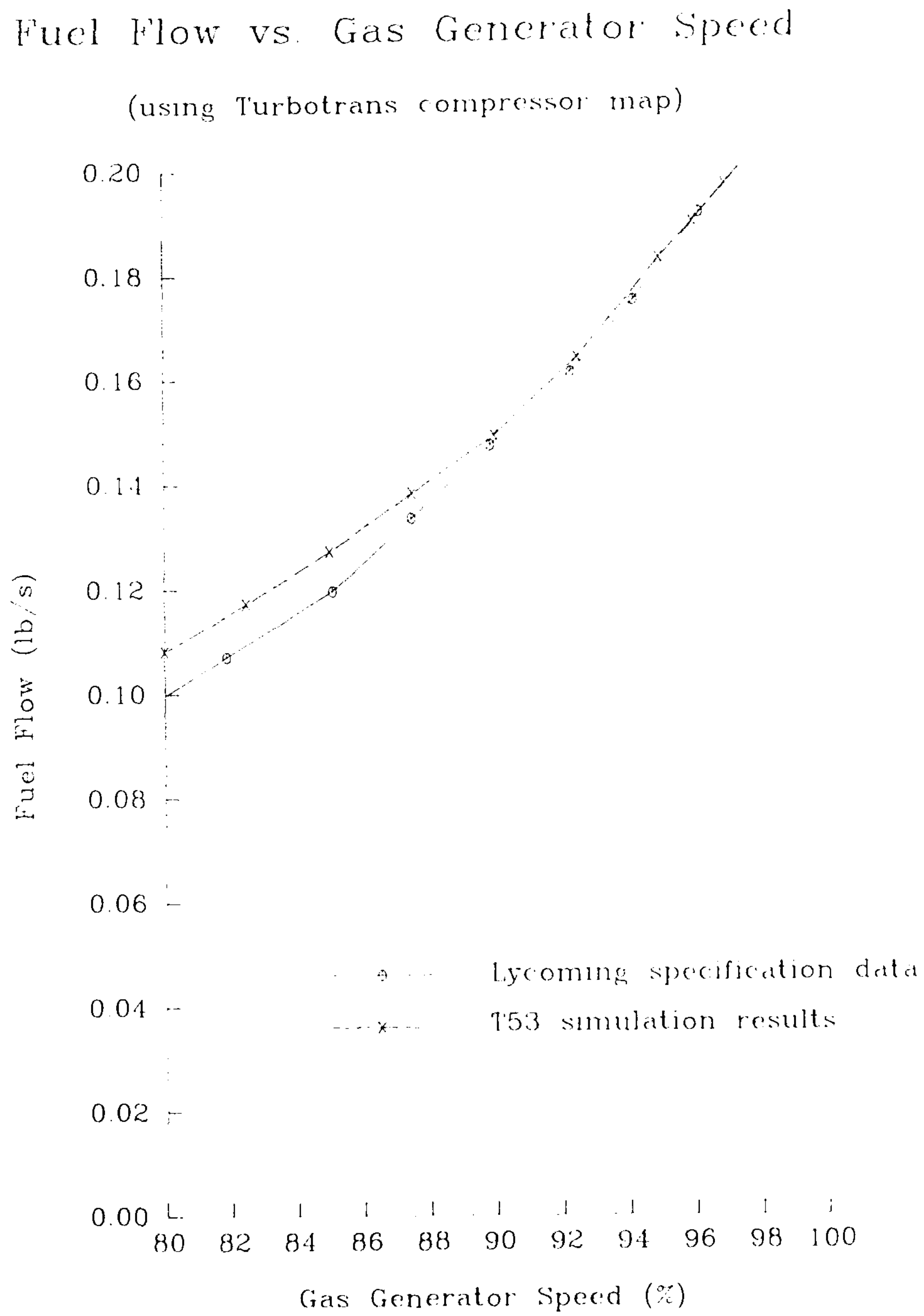
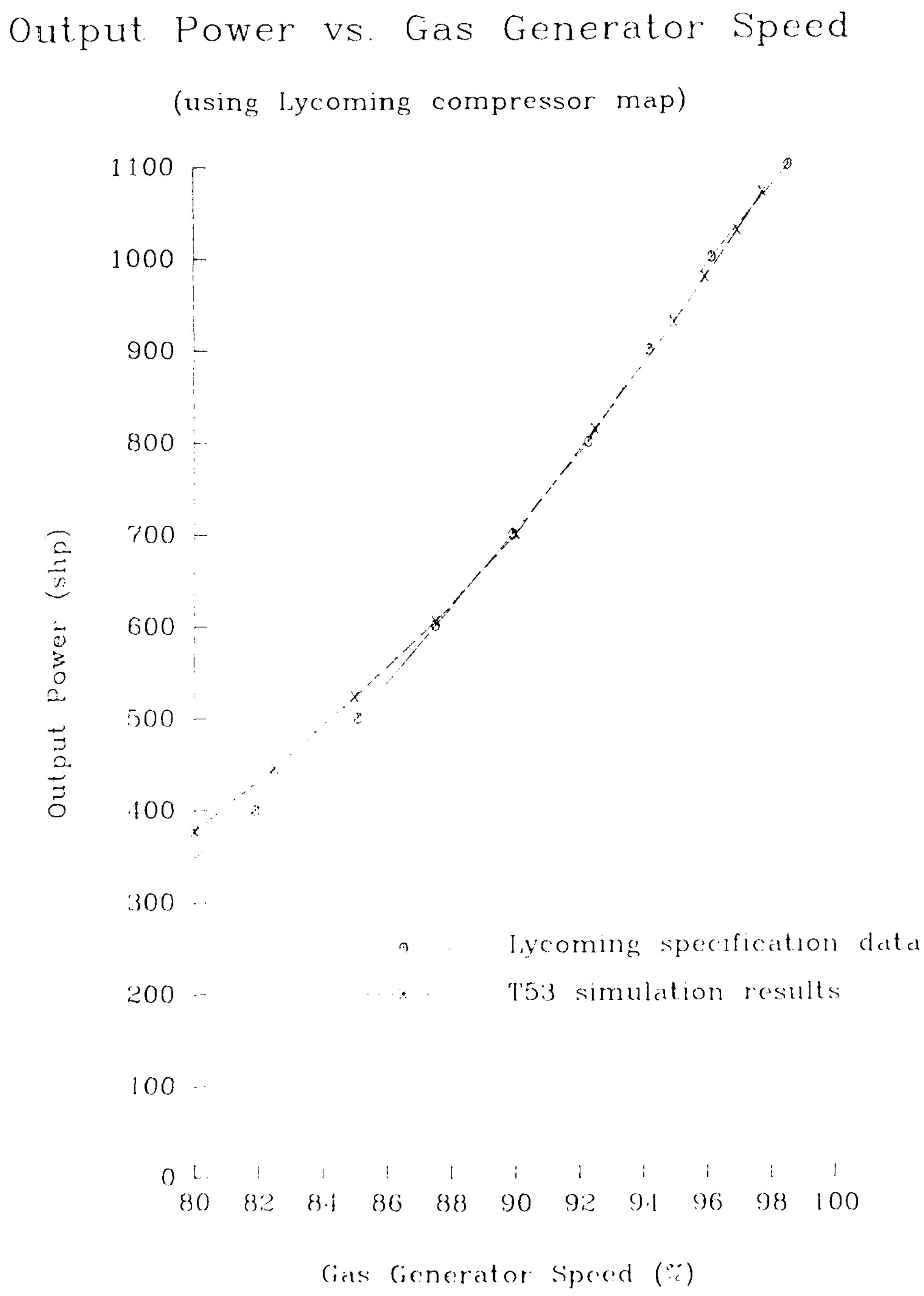


Figure 5



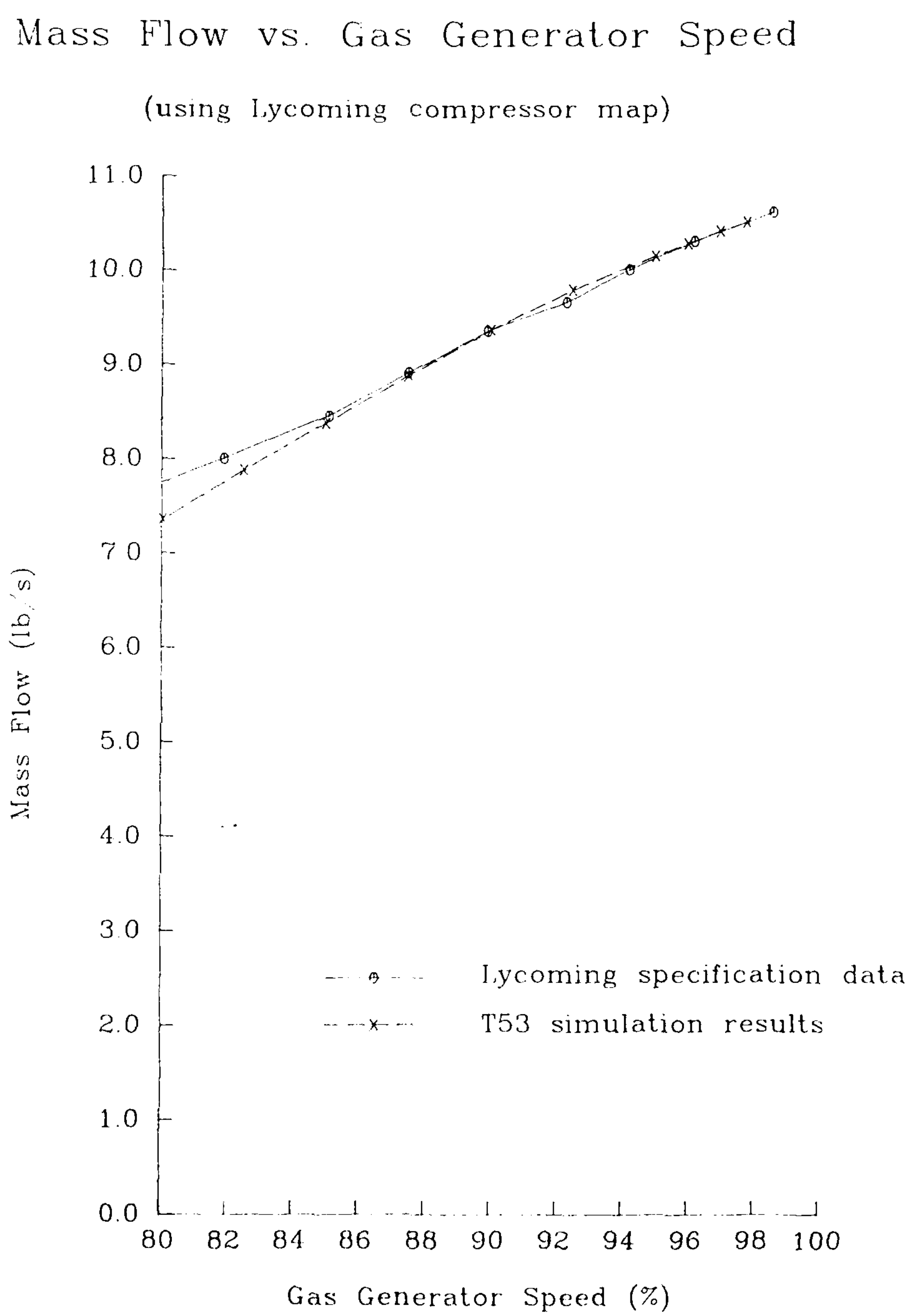
Fuel Flow vs. Gas Generator Speed
(using Turbotrans compressor map)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Fuel Flow (lb/s)
80
82
84
86
88
90
92
94
96
98
100
Gas Generator Speed (%)
Lycoming specification data
T53 simulation results

Figure 6



Output Power vs. Gas Generator Speed
(using Lycoming compressor map)
Output Power (shp)
1100
1000
900
800
700
600
500
400
300
200
100
0
80
82
84
86
88
90
92
94
96
98
100
Gas Generator Speed (%)
Lycoming specification data
T53 simulation results

Figure 7



Mass Flow vs. Gas Generator Speed
(using Lycoming compressor map)
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Mass Flow (lb./s)
80
82
84
86
88
90
92
94
96
98
100
Gas Generator Speed (%)
Lycoming specification data
T53 simulation results

Figure 8

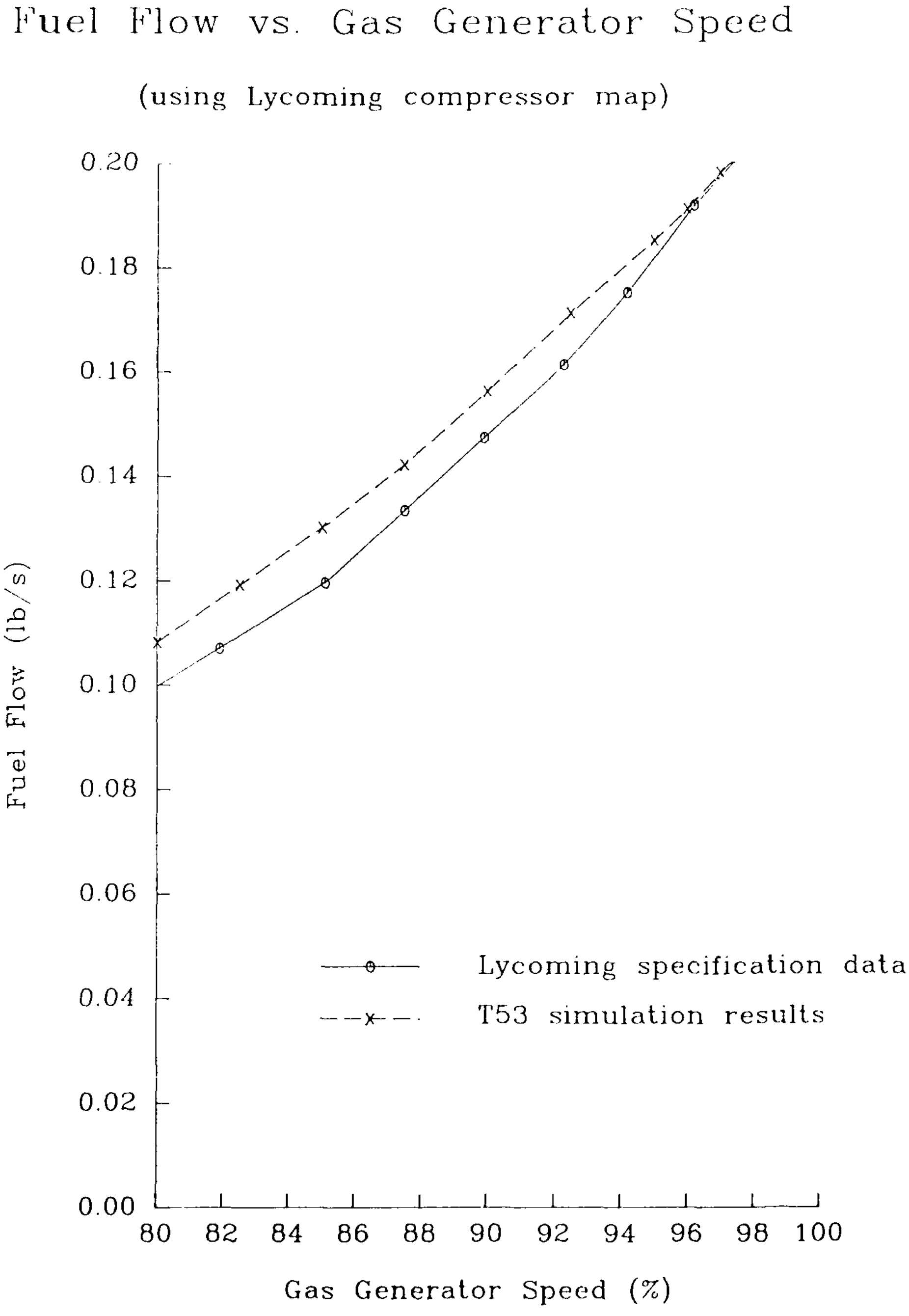

Fuel Flow vs. Gas Generator Speed
(using Lycoming compressor map)
Fuel Flow (lb/s)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
80
82
84
86
88
90
92
94
96
98
100
Gas Generator Speed (%)
Lycoming specification data
T53 simulation results

Figure 9

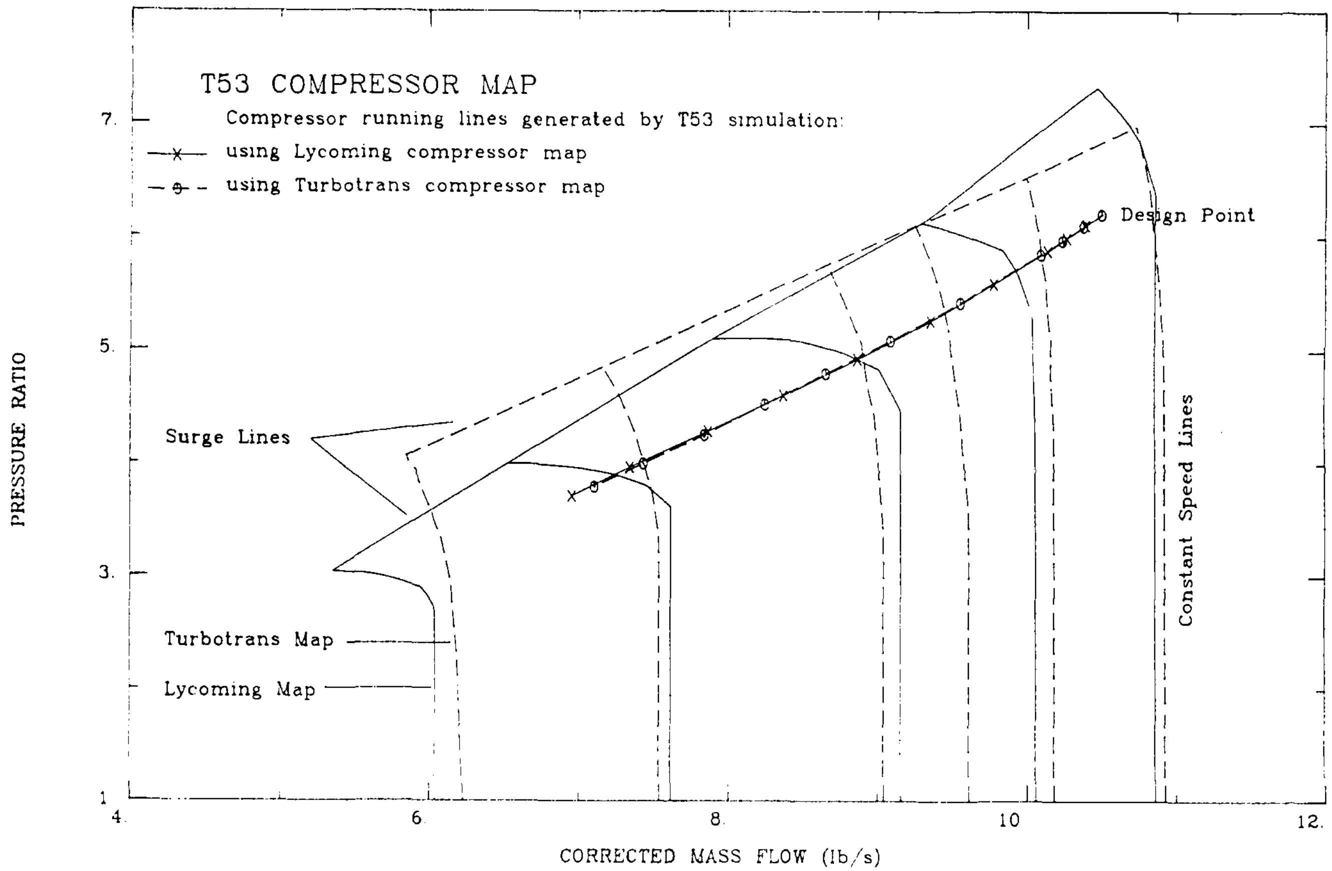

T53 COMPRESSOR MAP
Compressor running lines generated by T53 simulation:
using Lycoming compressor map
using Turbotrans compressor map
Design Point
Surge Lines
Turbotrans Map
Lycoming Map
Constant Speed Lines
PRESSURE RATIO
CORRECTED MASS FLOW (lb/s)
1
3.
5.
7.
4.
6.
8.
10
12.

Figure 10

Output Power vs. Free Turbine Speed

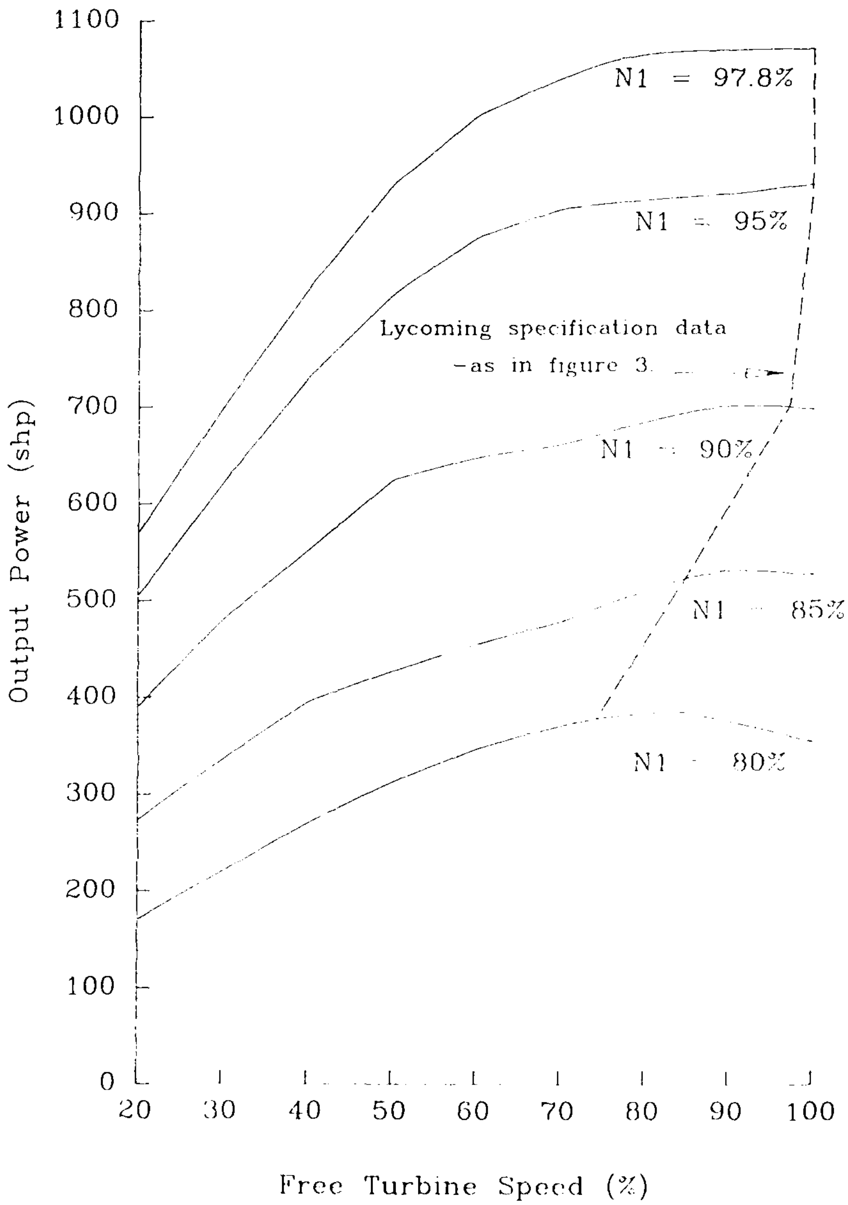


Figure 11

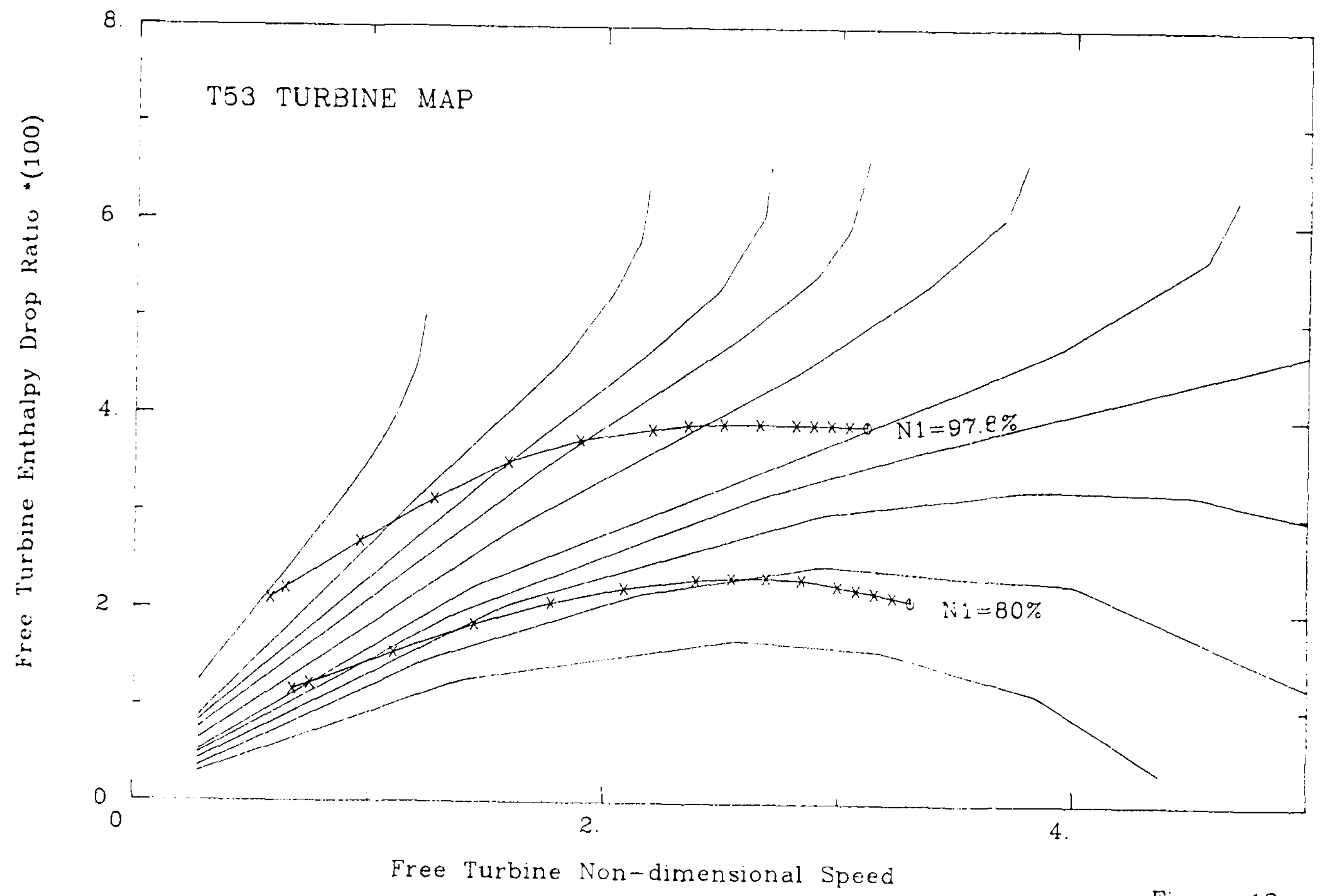

T53 TURBINE MAP
N1=97.8%
N1=80%
Free Turbine Enthalpy Drop Ratio *(100)
Free Turbine Non-dimensional Speed
0
2
4.
6
8.
0
2.
4.

Figure 12

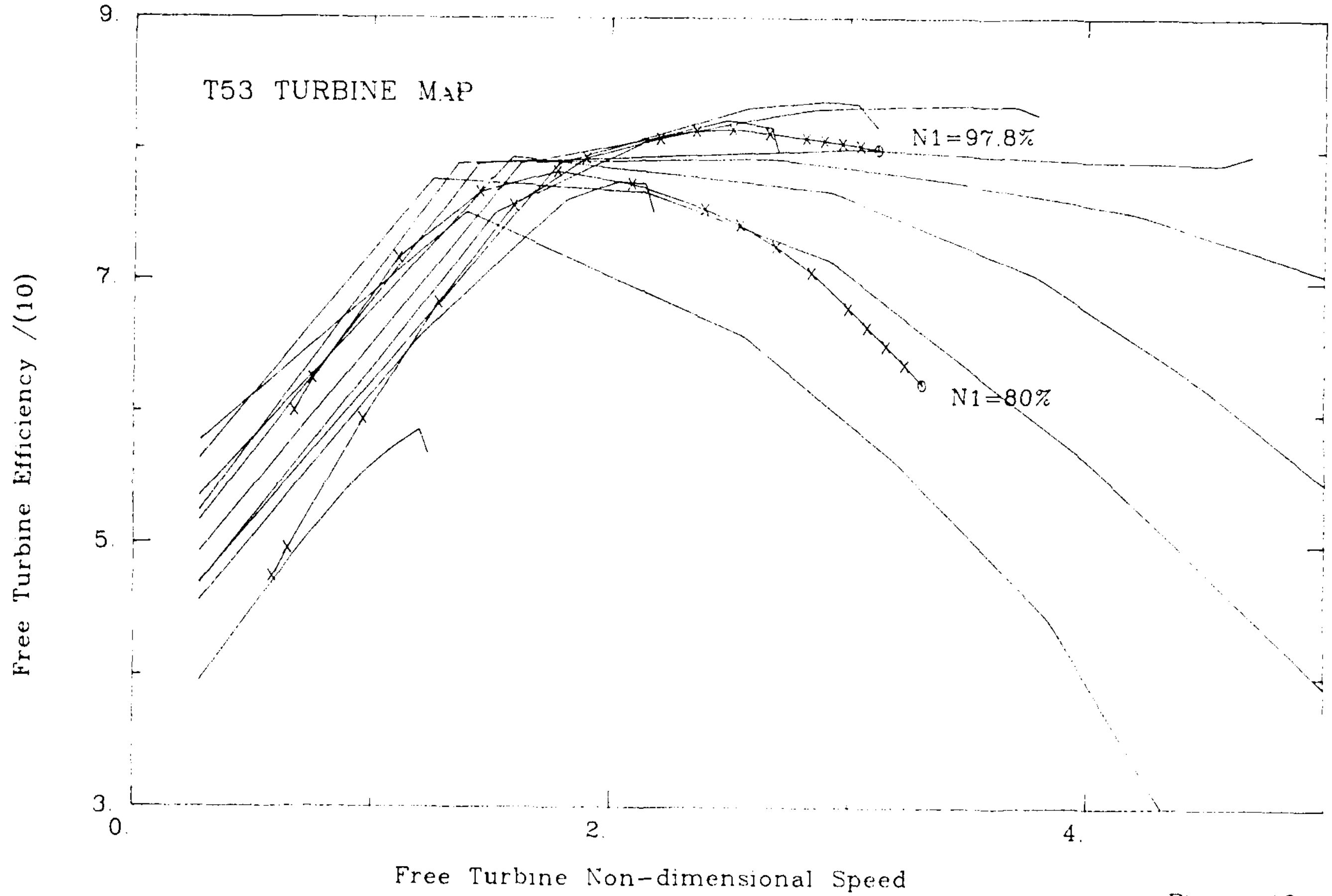
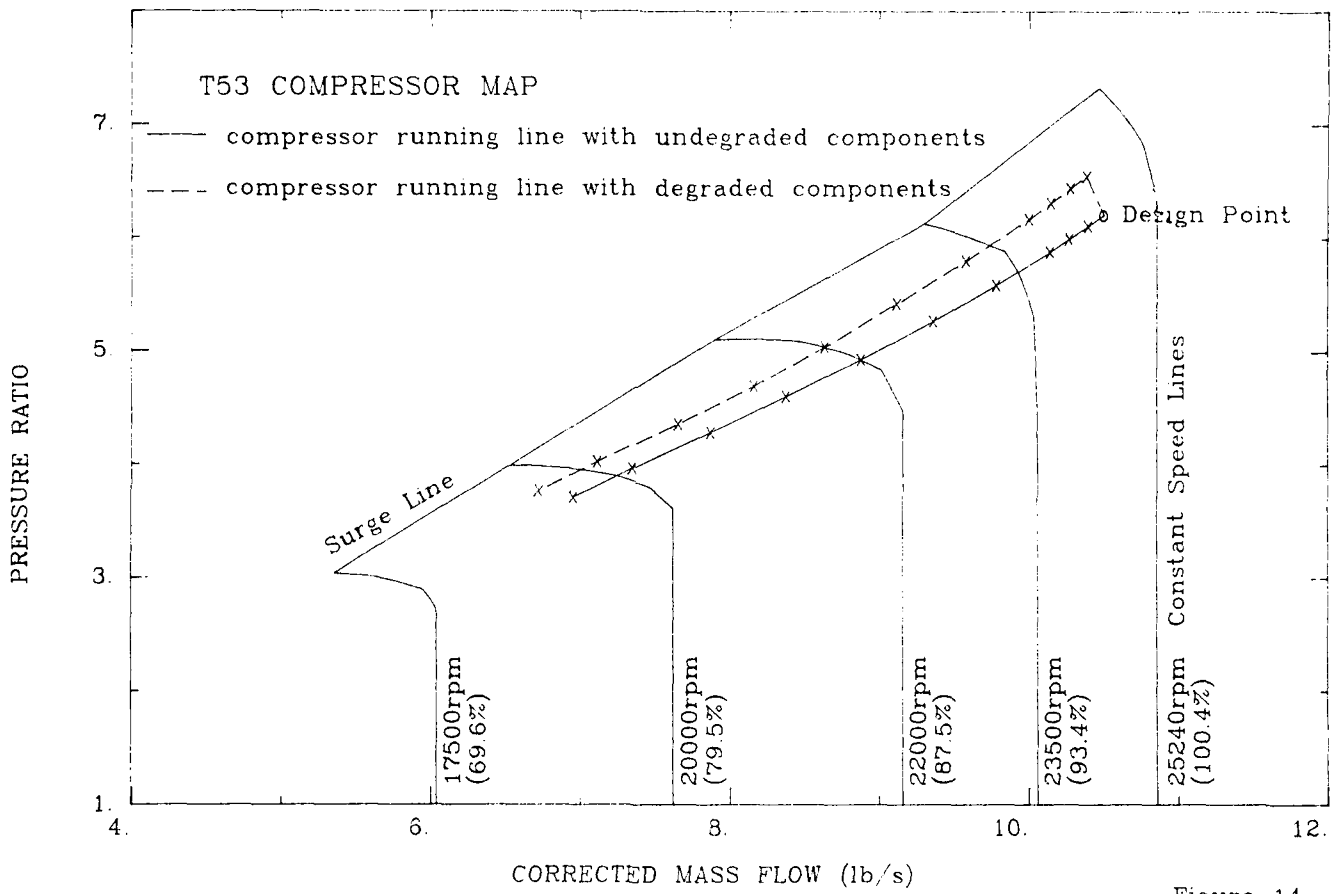

T53 TURBINE MAP
N1=97.8%
N1=80%
9.
7.
5.
3.
0.
2.
4.
Free Turbine Efficiency /(10)
Free Turbine Non-dimensional Speed

Figure 13



T53 COMPRESSOR MAP
compressor running line with undegraded components
compressor running line with degraded components
Design Point
Surge Line
Constant Speed Lines
17500rpm (69.6%)
20000rpm (79.5%)
22000rpm (87.5%)
23500rpm (93.4%)
25240rpm (100.4%)
PRESSURE RATIO
1.
3.
5.
7.
4.
6.
8.
10.
12.
CORRECTED MASS FLOW (lb/s)

Figure 14

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16. ABSTRACT

This Technical Memorandum describes the development of a steady-state engine model for a Lycoming T53 turboshaft engine. A genuine compressor map obtained from Lycoming was integrated into a generic gas turbine modelling program called Turbotrans. Both engine performance predictions and the variation of output power with free turbine speed showed good correlation with manufacturer's data. The ability to simulate engine wear and damage via degraded component efficiencies was demonstrated but not validated.

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